Alfvén Cascades and Internal Transport Barriers on JET

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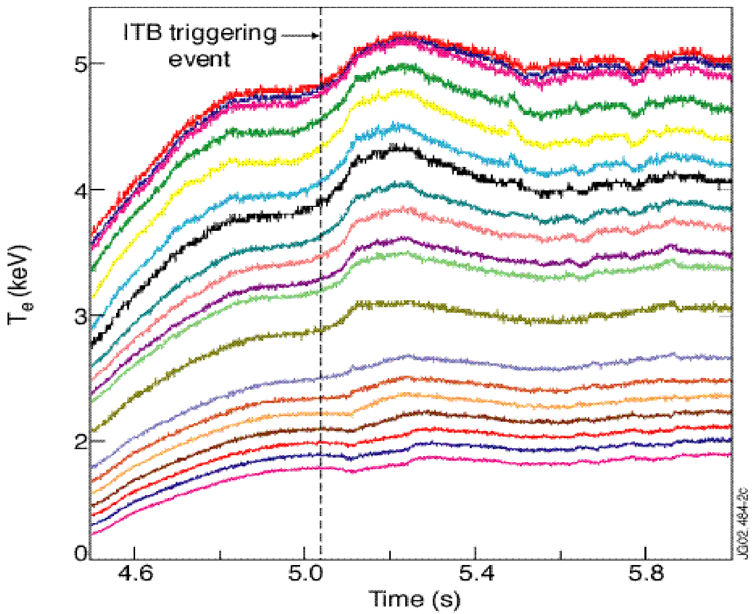
Internal Transport Barrier (ITB) Triggering Events



T_e measured with ECE. An increase in the slope is observed at t=5.1 s

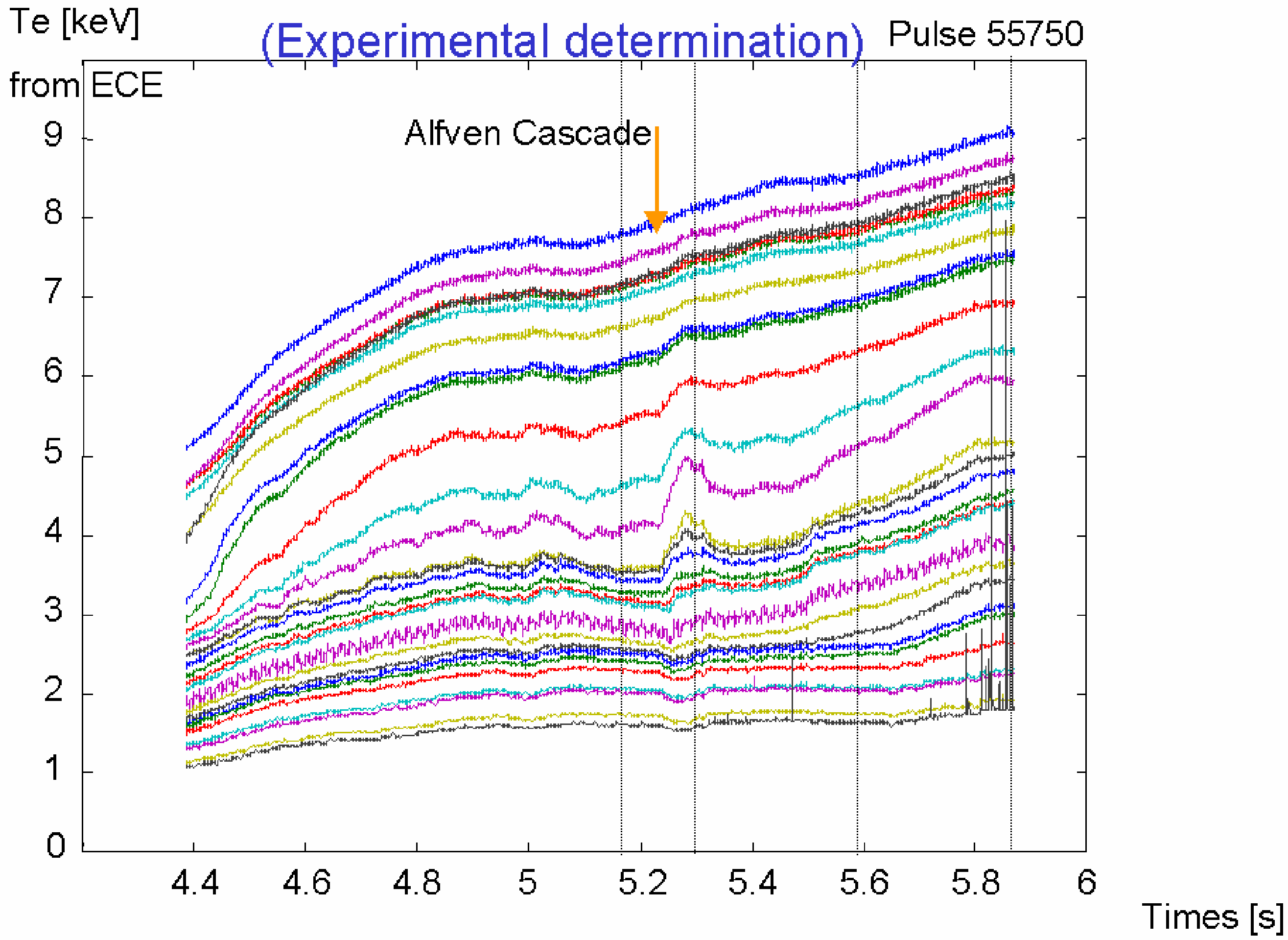
In JET shear-reversed discharges, ITB most often **starts** from q_{min} radius **when $q_{min}(t)$ passes an integer value**[1]

At later times, the ITB radius evolves **independently** of q_{min} position

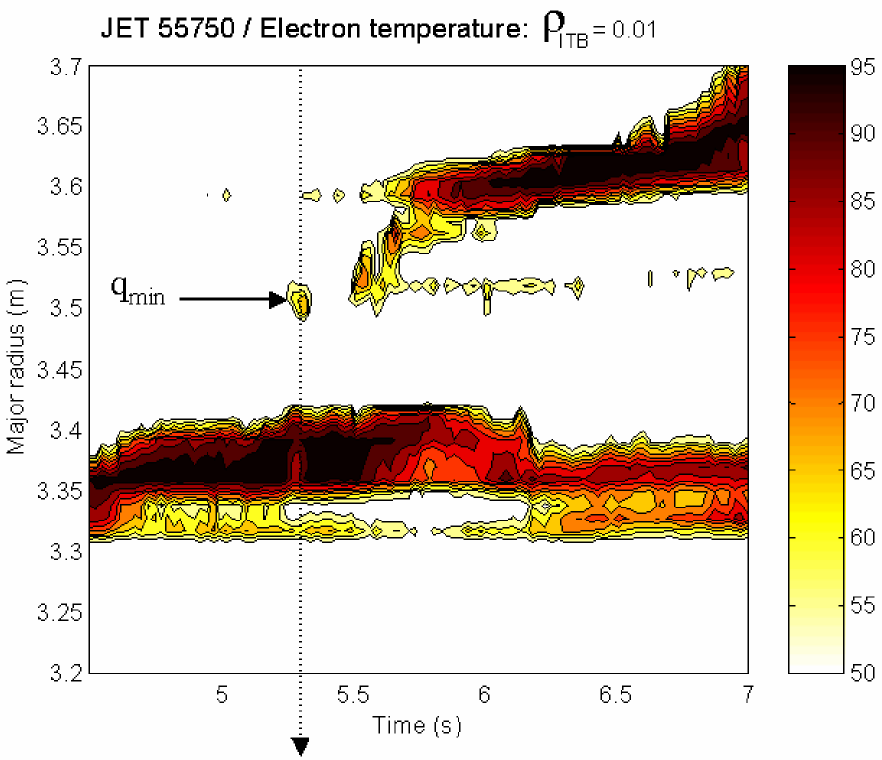
ITB starts from **ITB triggering event, observed as a sudden increase in dT_e/dt (at constant heating power)** when $q_{min}(t)$ passes an integer value

[1]E.Joffrin et al., Proceed of the 19th IAEA Conference, EX/P1-13, Lyon (2002)

ITB Triggering event in reversed magnetic shear



ITB criterion for pulse 55750



Triggering event and alfven cascade

$\rho_{ITB} \propto -C \cdot T_e^{-1/2} dT_e / dR$ (see Tresset et al., Nuclear Fusion 42, 520 (2002))

Aim:

- Develop diagnostics allowing to monitor $q_{min}(t)$ (not the whole profile q(r)!) in order to identify exact timing of the ITB triggering events

Technique: MHD spectroscopy, i.e.:

- Monitor Alfvén Cascades associated with q_{min} – these modes are easily excited by ICRH-accelerated ions in JET

Alfvén Cascades

- Radius of q_{min} is an **extremum** point for shear Alfvén waves $\omega^2 = \omega_A^2(r) \equiv k_\parallel^2(r)\, V_A^2\,(r)$:

$$\left.\frac{d\omega_A(r)}{dr}\right|_{r=r_{\min}} = 0,\quad V_A\,(r,t) \approx const$$

  so that an extremum of radial refraction index $N_r = ck_r/\omega$ can form a high-Q "waveguide" for shear Alfvén waves localised at q_{min}.
- These high-Q Alfvén waves form a **discrete spectrum**, due to the periodicity and boundary conditions, and are called **Alfvén Cascades** (ACs)[2,3]
- **AC** of mode numbers n, m has **frequency close to the extremum** value of shear Alfvén spectrum,

$$\omega_{AC}^2 \approx \omega_A^2(r_{\min}) \equiv k_{\parallel m}^2(r_{\min})\, V_A^2\,(r_{\min}),\quad k_{\parallel m}^2(r_{\min}) = \left| n - (m/q_{\min})^2 \right| / R_0^2$$

  and is localized[3] at the position of q_{min}

[2]S.E.Sharapov et al., Phys. Lett A289, 127 (2001)
[3]H.L.Berk et al., Phys. Rev. Lett 87, 185002 (2001)
[4]S.E.Sharapov et al., Phys. Plasmas 9, 2027 (2002)

Time evolution of $q_{min}(t)$, $k_{\parallel m}(t)$ and eigenfrequency of AC

- During the current ramp-up phase, $q_{min}(t)$ decreases, and $k_{\parallel m}(t)$ changes in time accordingly:

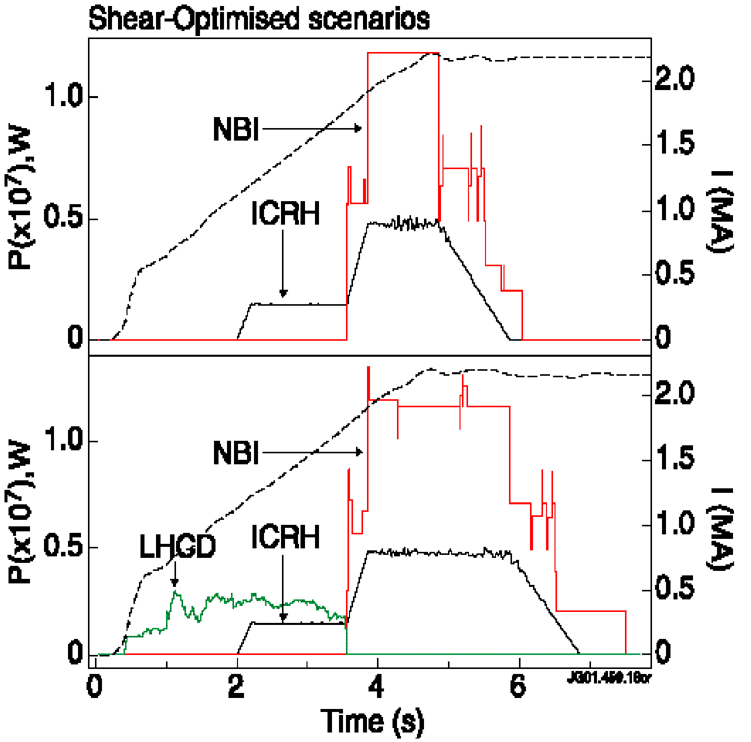
$$\frac{dk_{\parallel m}(r_{\min},t)}{dt} = \frac{m}{R_0}\frac{d}{dt}q_{\min}^{-1}(t)$$

- Since the frequency of an AC is close to the frequency of shear Alfvén wave at q_{min}, $\omega_{AC}^2 \approx k_{\parallel m}^2(r_{\min})\, V_A^2\,(r_{\min})$, the **AC frequency tracks the $q_{min}(t)$ evolution:**

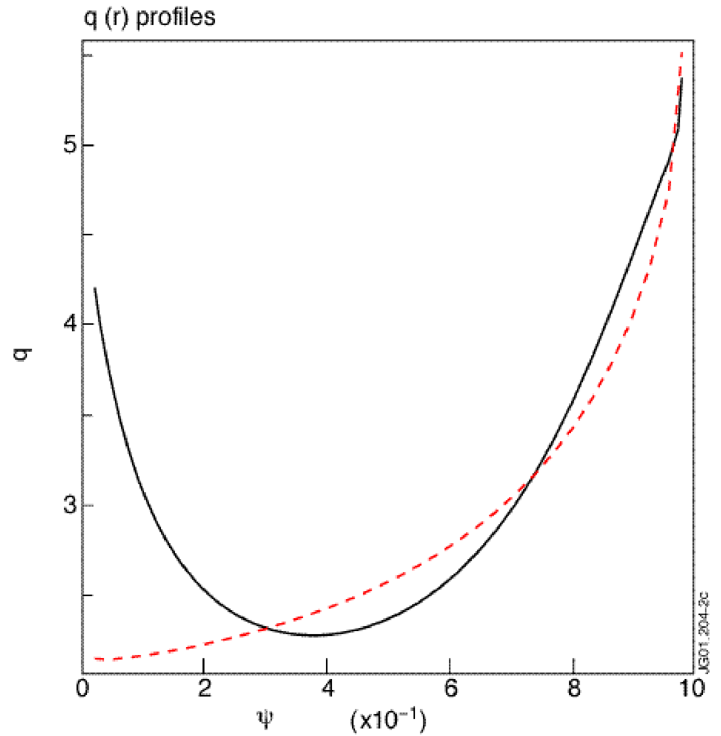
$$\frac{d\omega_{AC}(t)}{dt} \approx \frac{d\left(k_{\parallel m}(r_{\min},t)V_A\right)}{dt} = m\frac{V_A}{R_0}\frac{d}{dt}q_{\min}^{-1}(t)$$

- ICRH-accelerated energetic ions easily excite Alfvén Cascades in JET. By observing Alfvén Cascades, we can **monitor $q_{min}(t)$ and identify the times favourable for the ITB triggering events.**

Positive and Negative Shear Plasmas



Top: Power and current waveforms for positive shear plasma #49384
Bottom: Power and current waveforms for negative shear plasma #49382



$q(r)$-profiles for positive shear plasma #49384 and for negative shear plasma #49382

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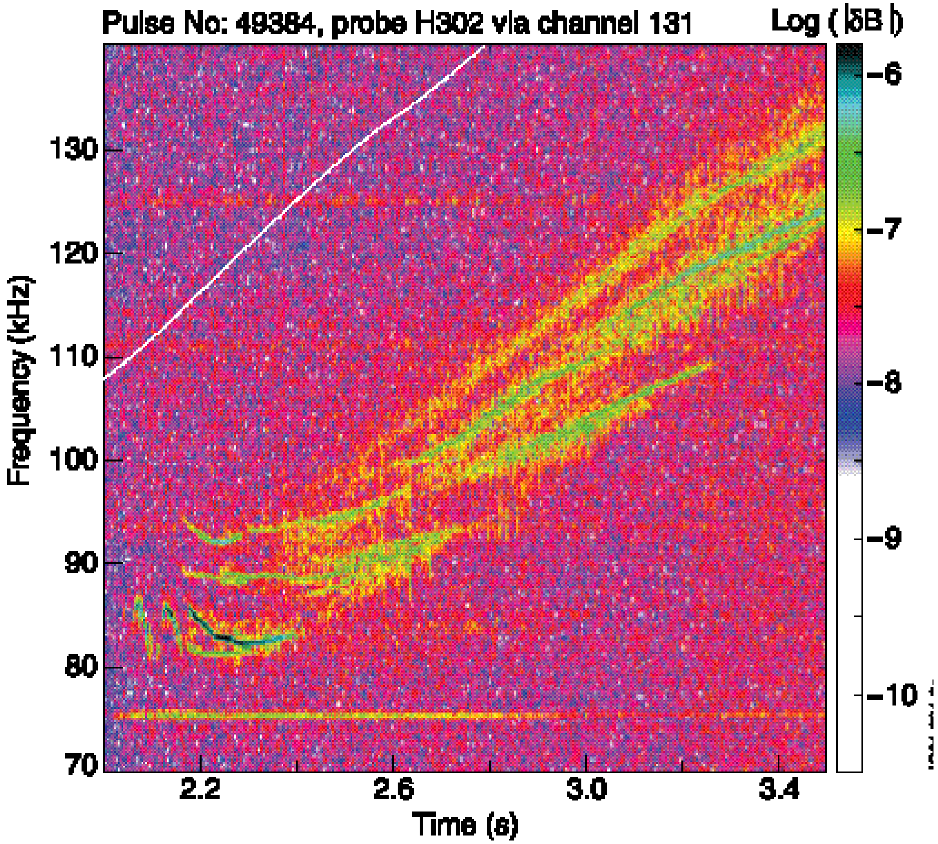
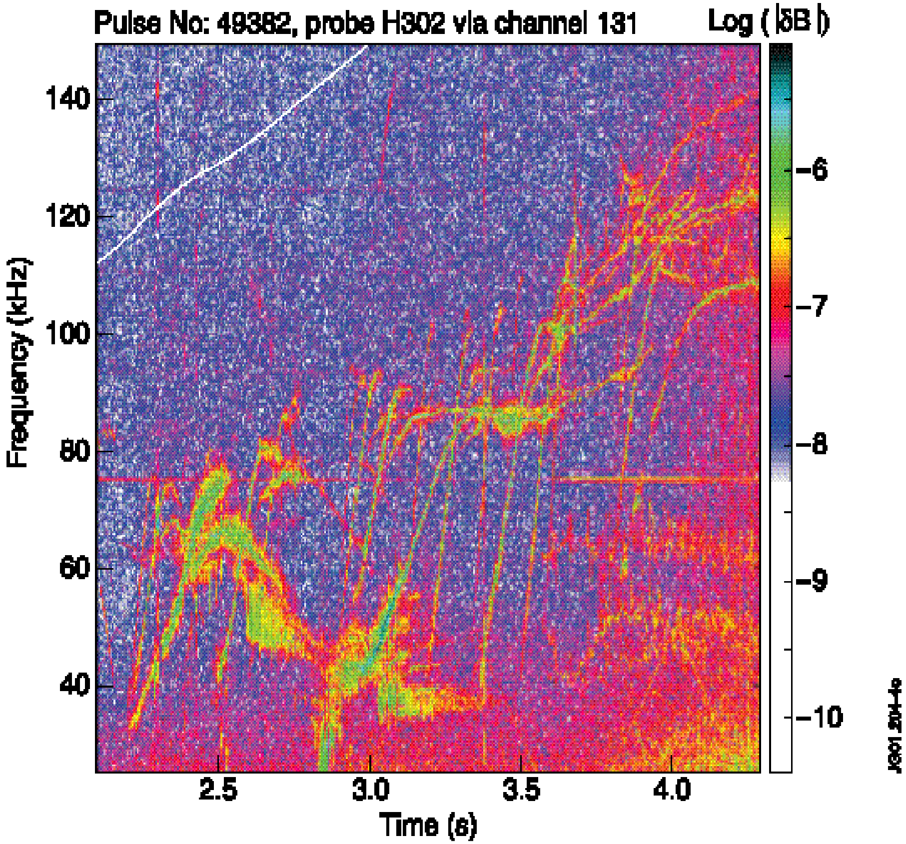
Measured Spectrum of Alfvén Waves Excited by ICRH-accelerated Ions



TAE modes observed in pulse #49384 with monotonic q(r)-profile



Alfvén Cascades observed in reversed-shear pulse #49382

S.E.Sharapov et al., 8th IAEA TM on Energetic Particles, 6-8 October 2003, San-Diego.

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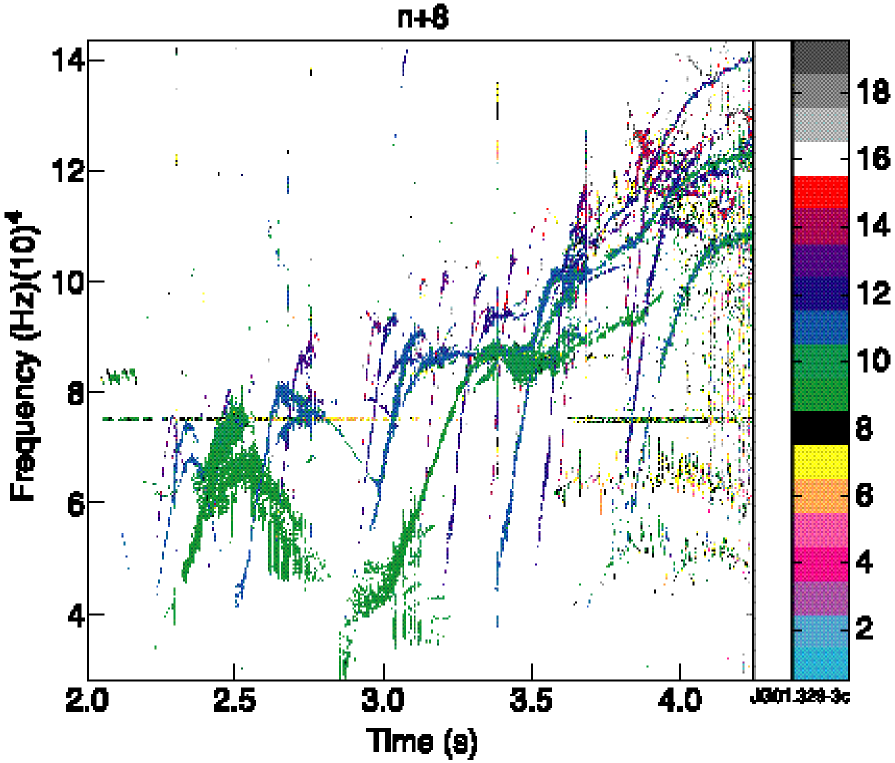
Properties of Alfvén Cascades



Magnetic perturbations in JET with non-monotonic q(r). **ACs** of n=1 to n=6 are observed **below TAE** frequency.

1) Each cascade may consist of **many modes** with different *n*'s from *n*=1 to *n*=6

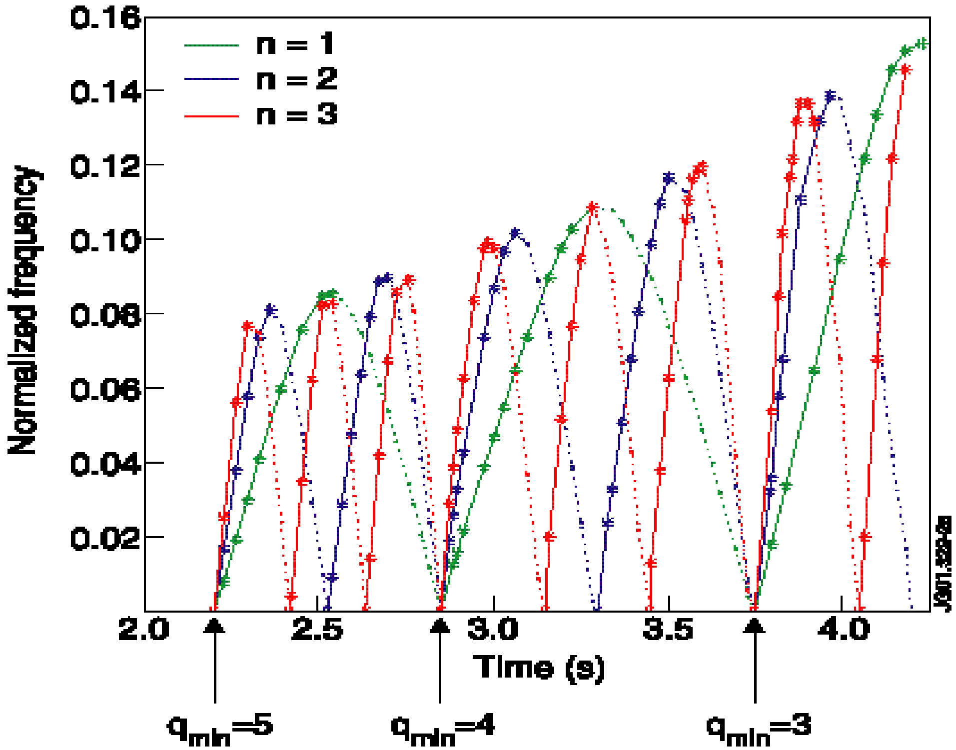
2) The modes with **higher mode numbers** exhibit a **more rapid frequency sweeping,** $df/dt \propto n$.

3)The **higher** *n* modes **re-occur more often** than the lower *n* modes

4) Internal ECE measurements show that **Alfvén Cascades are localised at** q_{min}

Time Evolution of Alfvén Continuum Tip at q_{min}

$$\omega_{ALfven}(r_{\min},t) = k_{\|m}(r_{\min},t)\ V_A(r_{\min},t)\,,\quad k_{\|m}(r_{\min},\ t) = \frac{1}{R}\left|n - \frac{m}{q(r_{\min},\ t)}\right|,$$



Comments on theory of Alfvén Cascades

$$\omega_{AC} = \left|k_{\parallel m}(r_{\min}, t)\right| V_A(r_{\min}, t) + \delta\omega\left(d\langle n_{hot}\rangle / dr,\ d^2 q / dr^2, \ldots\right)$$

The mode exists if[5] $Q = Q_{hot} + Q_{tor} > 1/4,$

Energetic ion contribution $Q_{hot} = -\dfrac{4\pi e_h R_0^2 q_{\min}^3 \omega}{c B r_{\min} q''_{\min}(m - n q_{\min})} \dfrac{\partial\langle n_h\rangle}{\partial r}\Big|_{r=r_{\min}}$

Toroidicity effect $Q_{tor} = \dfrac{\omega^2}{2} \dfrac{R_0^2}{V_A^2(1 - n q_{\min}/m)} \dfrac{q^3{}_{\min}}{r_0^2 q''_{\min}} \dfrac{\varepsilon_0(\varepsilon_0 + 2\Delta')}{1/4 - (m - n q_{\min})^2}$

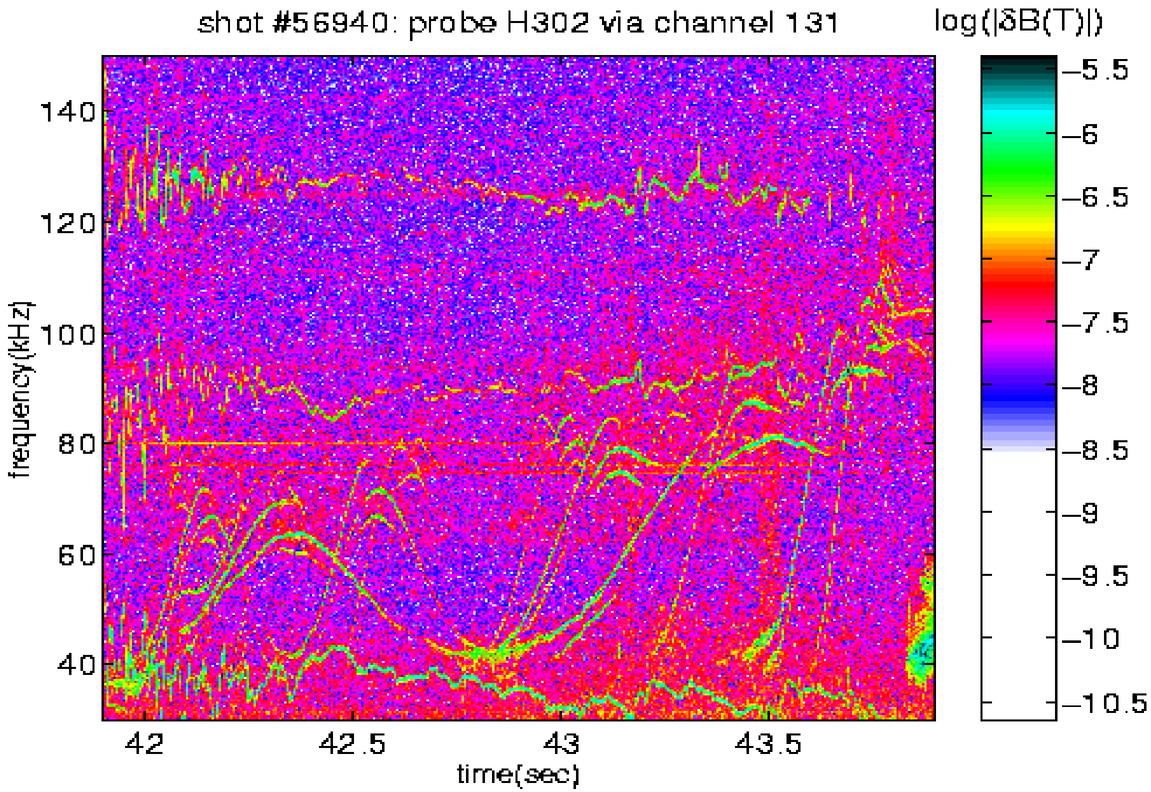
Q_{hot} dominates for ACs driven by ICRH-accelerated ions in JET ($n_h/n_e \sim 10^{-3} \div 10^{-2}$):

$$\frac{Q_{hot}}{Q_{tor}} \approx \frac{\omega_{Bh}}{\omega} \frac{n_h}{n_e} \frac{r}{L_h} \frac{1}{m\varepsilon^2 q_{\min}} \left(\frac{1}{4} - (m - n q_{\min})^2\right) \approx (10 \div 100) \frac{1}{q_{\min}^2} \left(\frac{1}{4} - (m - n q_{\min})^2\right)$$

However, Q_{tor} was dominant in ACs driven by low-density alpha-particles in TFTR[6]

[5] B.N.Breizman et al., Phys. Plasmas 10, 3649 (2003)
[6] R.Nazikian et al., to be published in Phys. Rev. Lett. (2003)

Comments on theory of Alfvén Cascades



"Sinusoidal" Alfvén Cascades (very rare!) remain yet unexplained (more in B.Breizman's talk)

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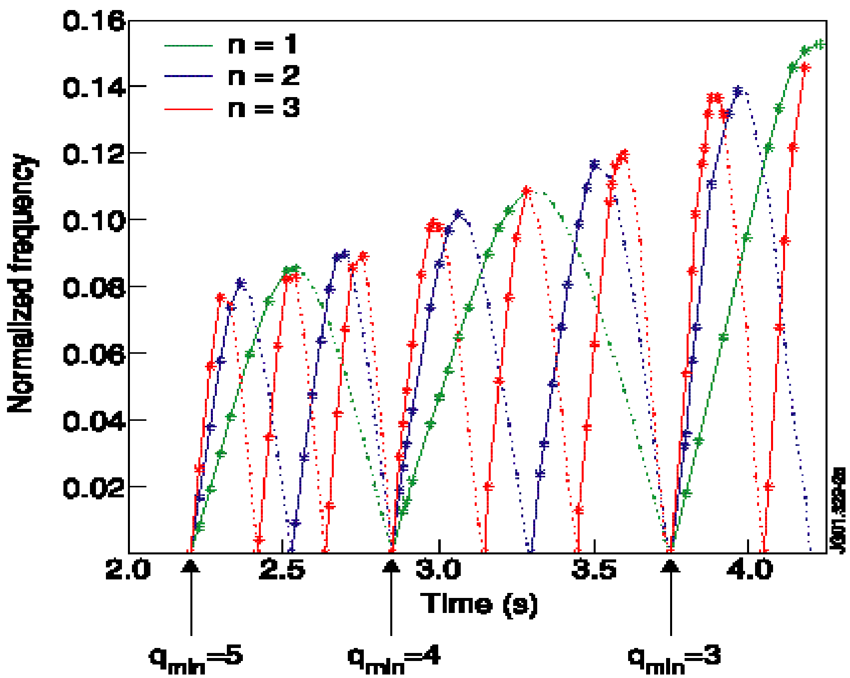
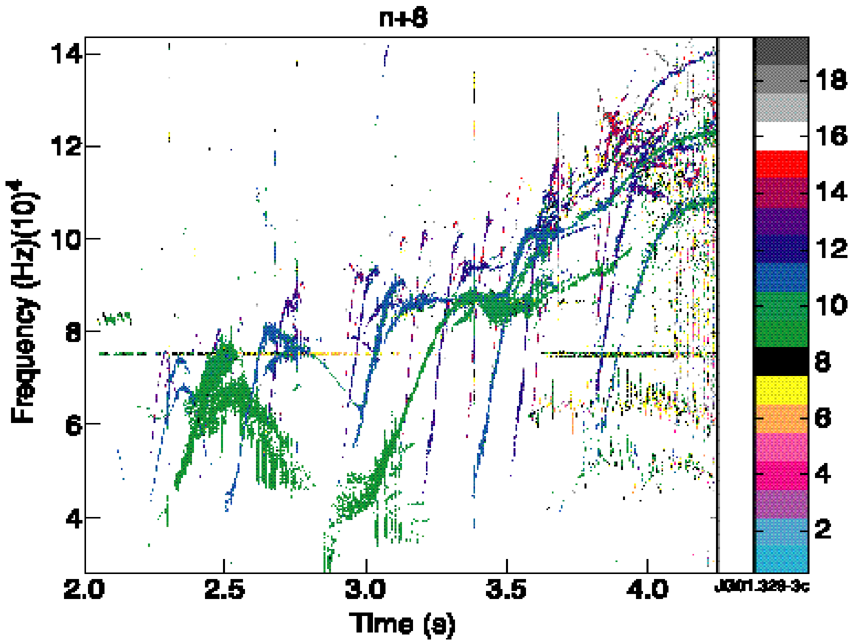
Time Evolution of Alfvén Continuum Tips vs Experimental Data



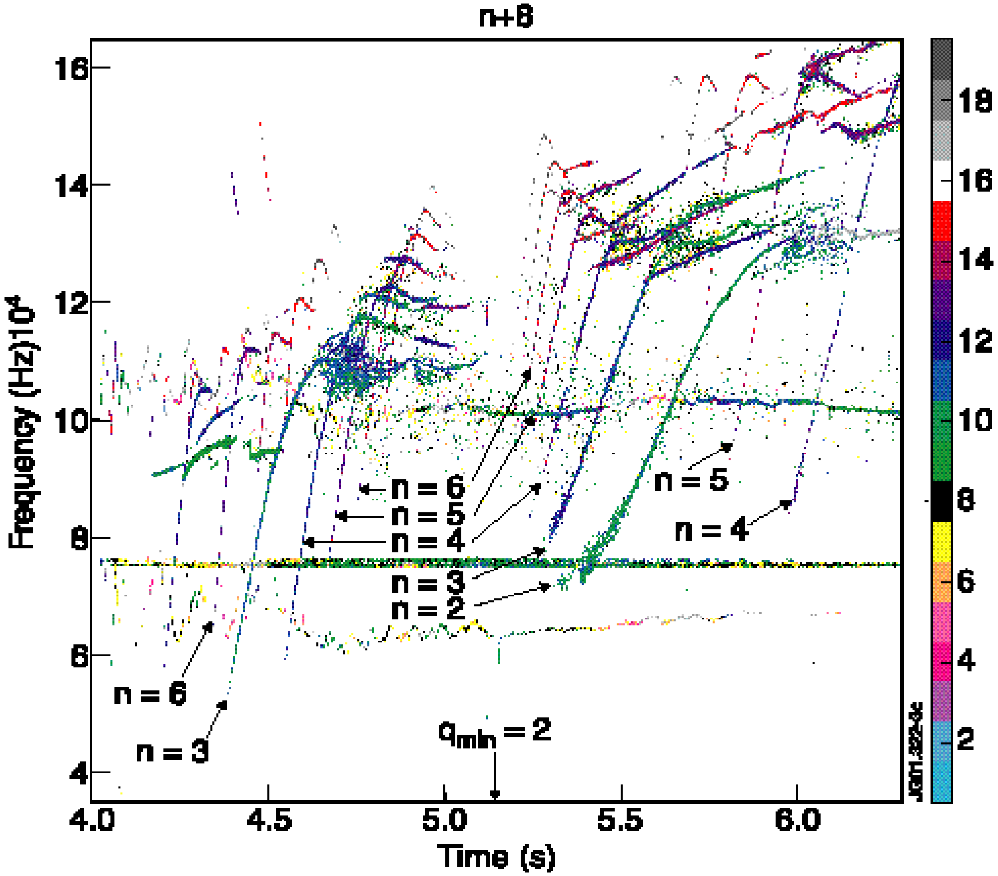
CSCAS: the evolution of **n=1**, n=2, and **n=3** continuum tips during $q_{min}(t)$ evolution



Alfvén Cascades observed in JET reversed-shear pulse #49382

$$\omega_{AC}(t) = \left| \frac{m}{q_{\min}(t)} - n \right| \frac{V_A(t)}{R_0} + \Delta\omega$$

MHD spectroscopy from clustering of different *n*'s in time



Condition for Alfvén cascade to appear:

$$m - nq_{\min}(t) = 0,$$

n and m are integers

$\Downarrow$

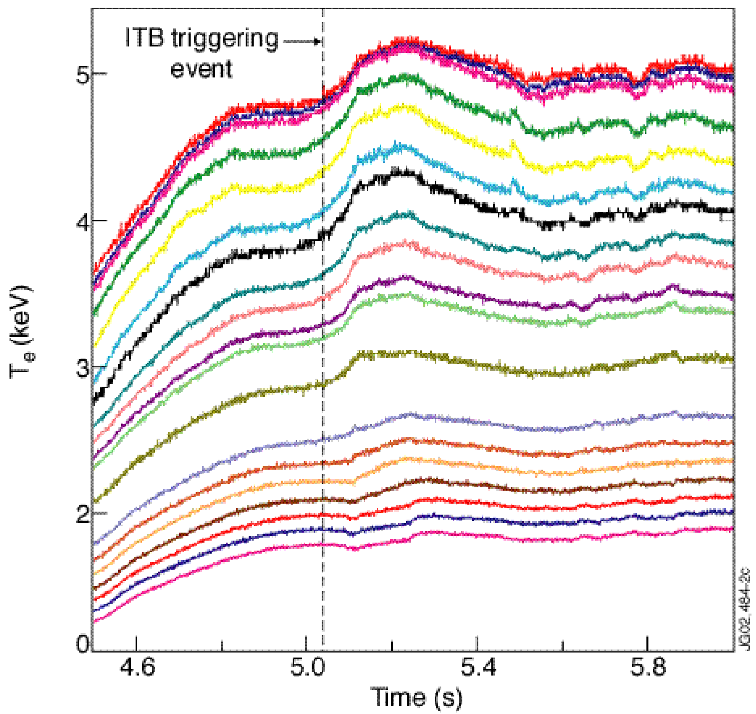
***n*=1** ACs occur when **q_{min}=1,2,3…;**

***n*=2** ACs occur when **q_{min}=1, 3/2, 2, 5/2, 3…;**

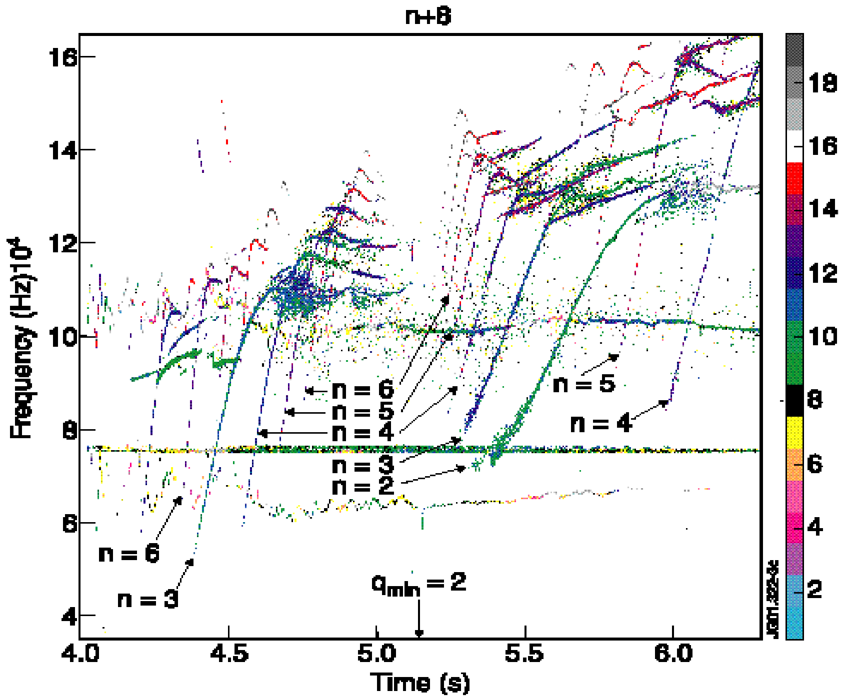
***n*=3** ACs occur when **q_{min}=1, 4/3, 5/3, 2, 7/3, 8/3, 3…**

Alfvén Cascade, in which all n's are present $\Rightarrow$ **Grand Cascade**. It occurs when $q_{\min}(t)$ passes an integer value.

Alfvén Grand-Cascade as a Diagnostic Tool for ITB Triggering Event

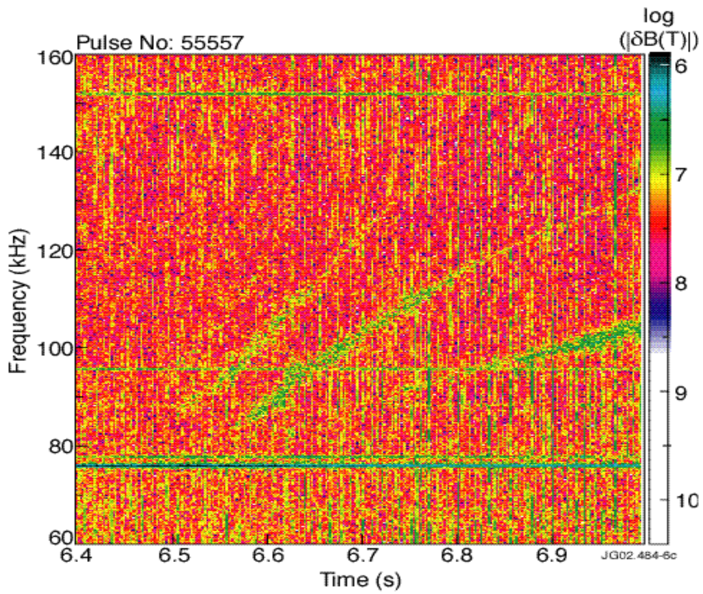


T_e measured with ECE. An increase in slope is observed at t=5.1 s

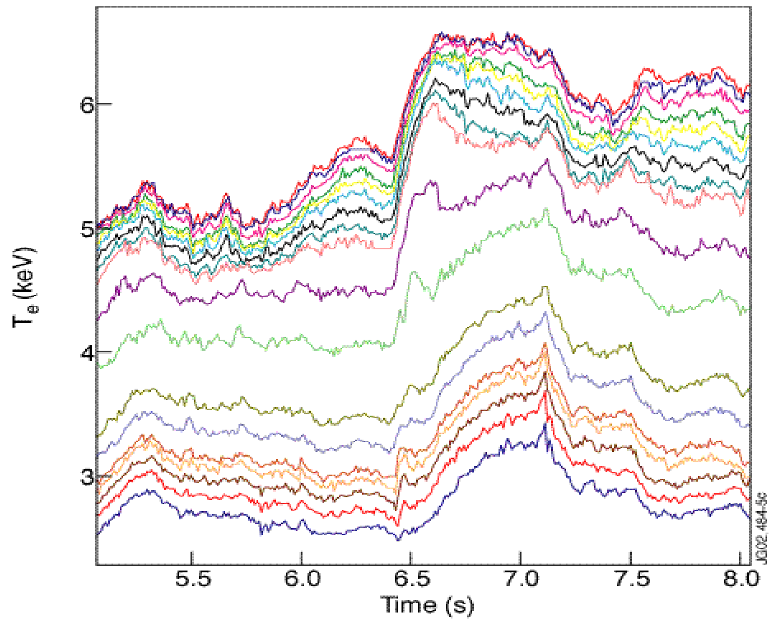


Alfvén grand-Cascade observed at t=5.15 s

Alfvén Grand-Cascade is visible even in high-noise plasmas

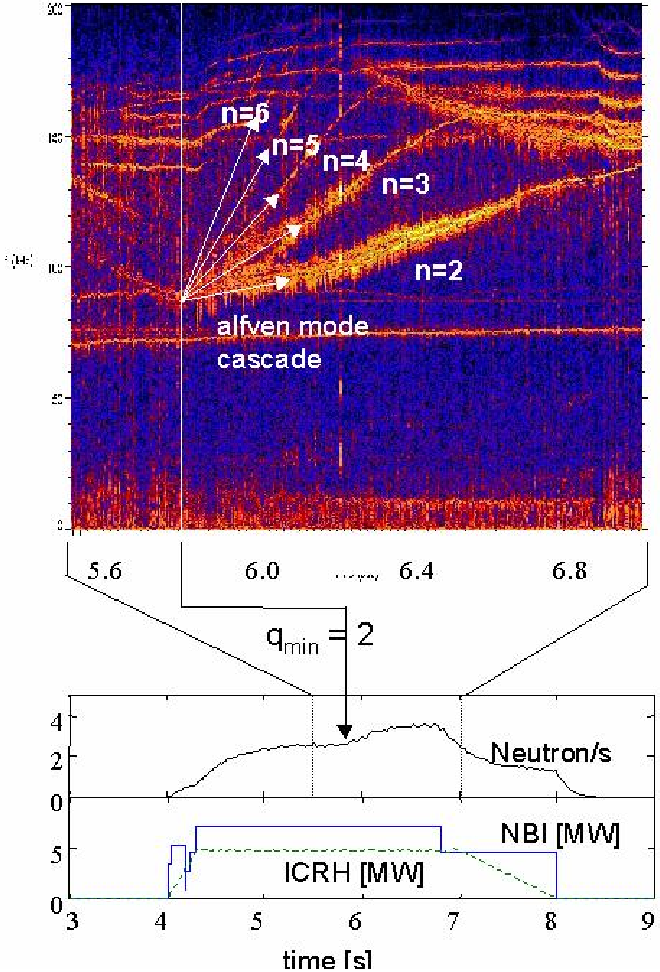


Magnetic spectrogram showing low-amplitude grand-cascade at t ~ 6.5 s in discharge #55557, B_T=2.45 and I_P=2.2 MA.



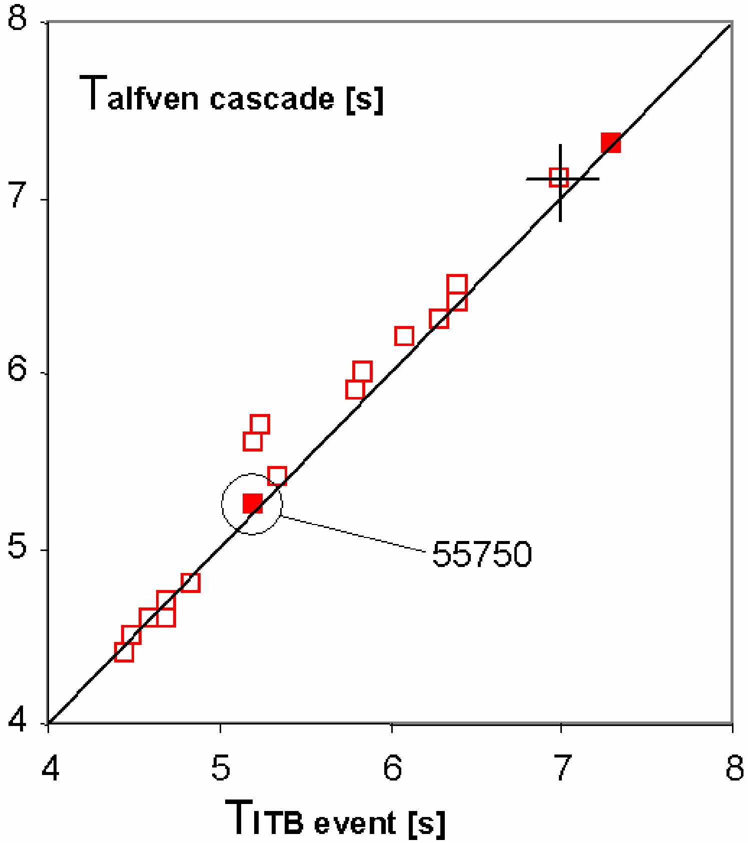
Electron temperature measured with ECE diagnostics in #55557. ITB triggering event is observed at t ~ 6.4 s

Correlation of Alfven cascades with ITB formation



(Pulse 51579)

Correlation Alfven cascade - ITB triggering event.



1- When Alfven cascade and triggering event are both observed, they occur at the same same within 0.2s.

2- This indicates that the triggering event is related to q_{min} reaching a rational surface.

3- This correlation is observed for a large variety of plasma conditions:

$1.5 < I_p < 2.8$ MA
$2.45 < B_T < 3.4$ T
$3 < P_{TOT} < 17$ MW

Alfvén grand Cascades versus the ITB triggering events

- Correlation between Alfvén grand-Cascades and the ITB triggering events was established in JET discharges with different types of the pre-heating, i.e. with
- LHCD,
- ICRH+LHCD,
- ICRH only,
- NBI only,
- with pellets

Developing ITBs via detecting Alfvén grand-Cascades

- For each scenario, run a probe discharge with 2-3 MW of ICRH only. Detect all the Alfvén grand-Cascades associated with integer q_{min} (usually q_{min} = 3, 2 are used)

- Identify the relevant times favourable for ITBs, i.e. $t(q_{min} = 3)$ and $t(q_{min} = 2)$

- In order to obtain ITB in subsequent discharges, repeat the probe discharge with main heating applied ~200 msec **before** the grand-Cascade time in the probe pulse

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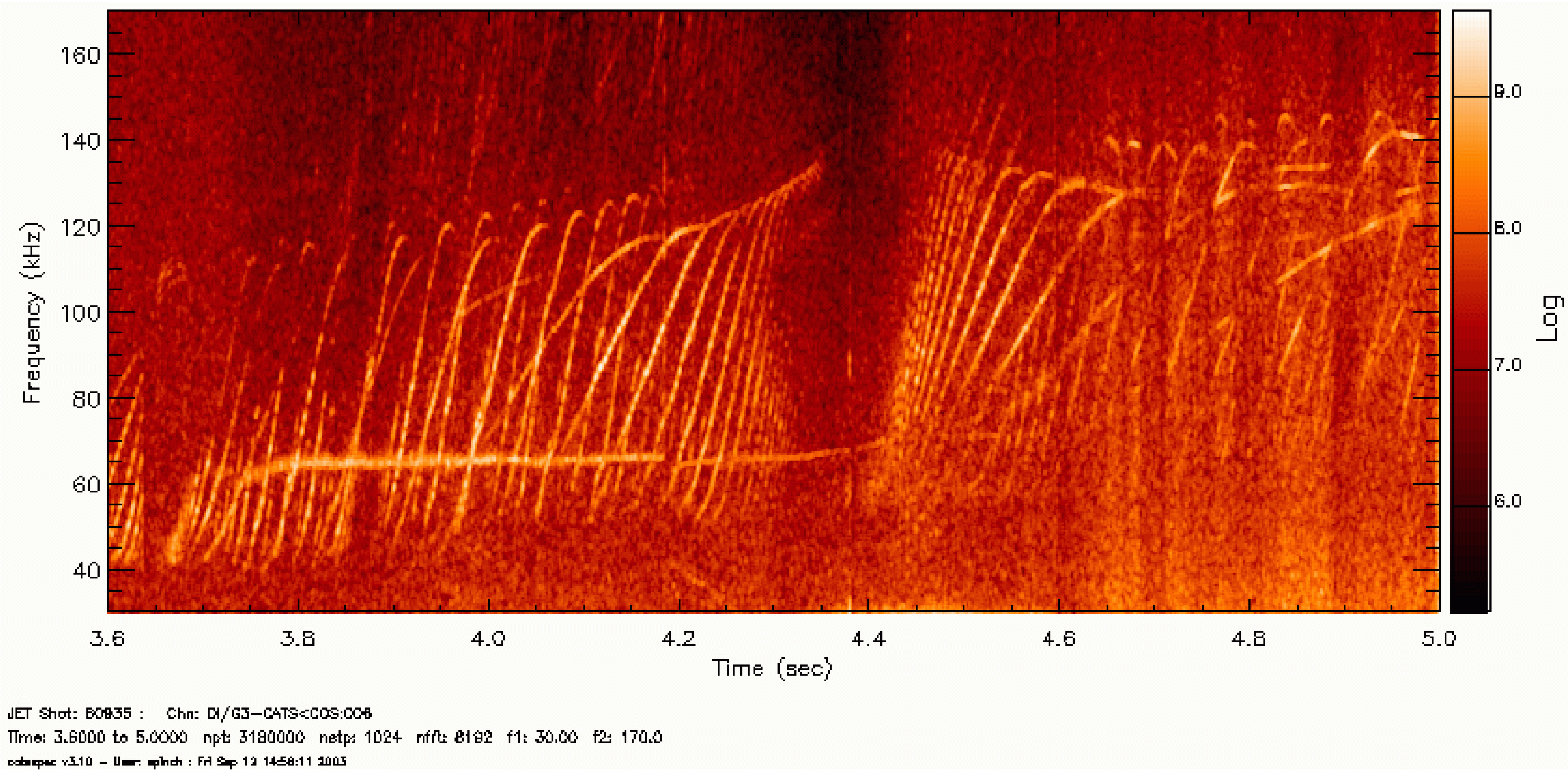
ACs show “density of rationals” in layer surrounding q_{min}:

Alfvén Cascades detected with O-mode reflectometry in interferometry mode



S.E.Sharapov et al., 8th IAEA TM on Energetic Particles, 6-8 October 2003, San-Diego.

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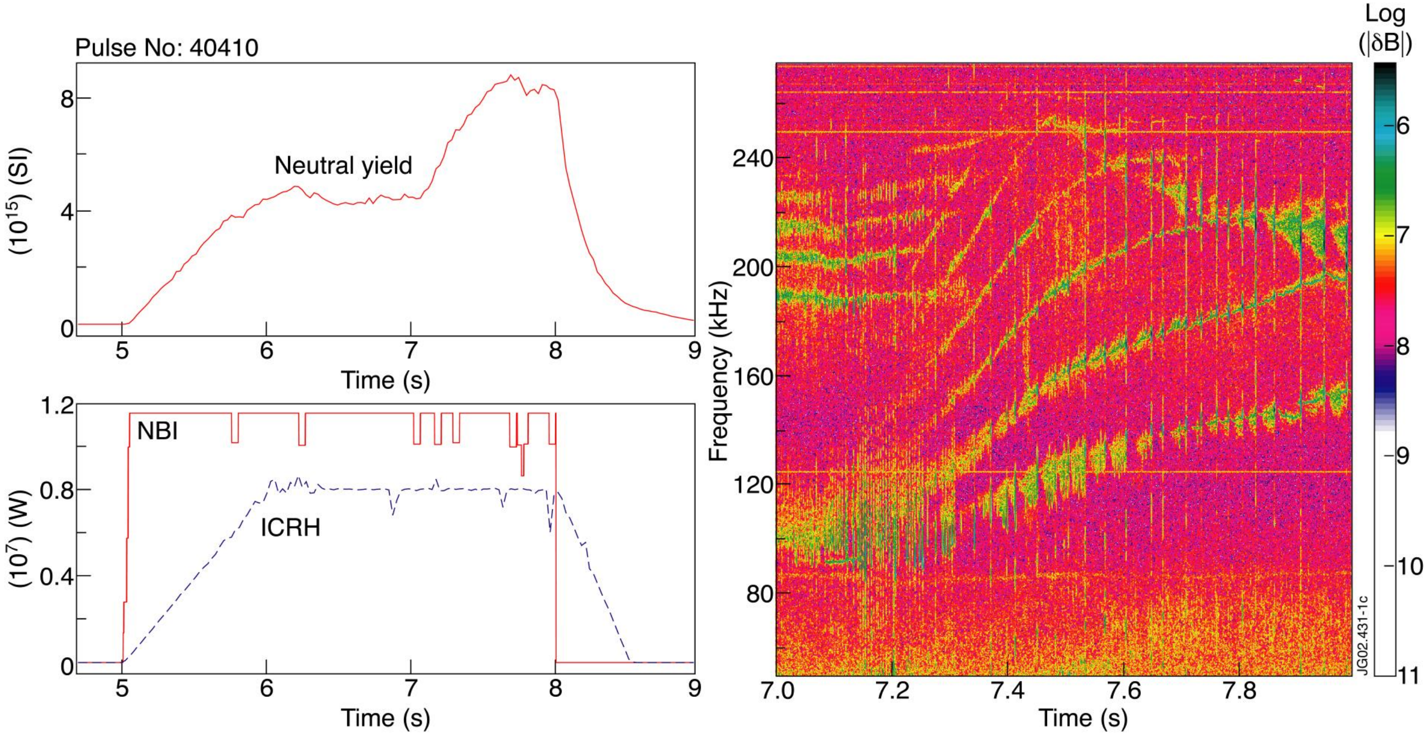
Back in history (1997): Alfvén Grand Cascade and ITB



Evolution of T_e, neutron yield, NBI and ICRH power in discharge #40410 B_T =3.4 T, I_P = 3 MA. Unidentified mode is detected at t=7.1 sec when the neutron yield takes off suddenly.

S.E.Sharapov et al., 8th IAEA TM on Energetic Particles, 6-8 October 2003, San-Diego.

Summary

- **Alfvén Cascades = modes associated with q_{min}** excited by fast ions.
- Used successfully for monitoring the $q_{min}(t)$ evolution
- The **temporal correlation** between Alfvén grand-Cascades, ITB triggering events and integer values of q_{min} has been **established for a wide range of plasma conditions** and pre-heating scenarios on JET
- A **technique for obtaining ITBs** in shear reversed plasmas by applying the main heating shortly before the AC time has been **established on JET**
- A **new way of detecting Alfvén Cascades with interferometry** has been found. These measurements give a high-accuracy monitoring of $q_{min}(t)$ and may lead to a systematic diagnosis of the transport properties of the layer surrounding q_{min}